



The Cryogenic Propellant Storage and Transfer Technology Demonstration Mission: Progress and Transition

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Outline



- ***Motivation for an in-space demonstration***
- ***Early mission concept formulation***
- ***External input (Broad Area Announcement contracts)***
- ***Mission overview & redirection***
- ***Technology maturation overview***
 - ***Thermal control technologies***
 - ***Propellant transfer***
 - ***Propellant gauging***
 - ***Analytical modeling***
- ***Summary***

CPST Demonstration Cross-Cutting Benefits

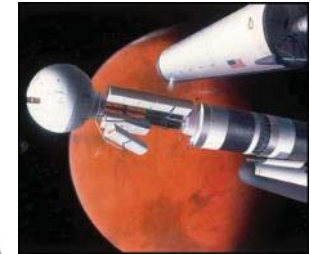


Extended
Commercial
Upper Stage
Capabilities

High-
Performance
Chemical
Propulsion
Beyond LEO



ISRU
Propellant
Storage &
Utilization



Nuclear Thermal
Missions to Mars

Cryogenic Storage, Expulsion, & Transfer Technologies

Safer, Faster Ground
Processing



Advanced Thermal
Management Systems



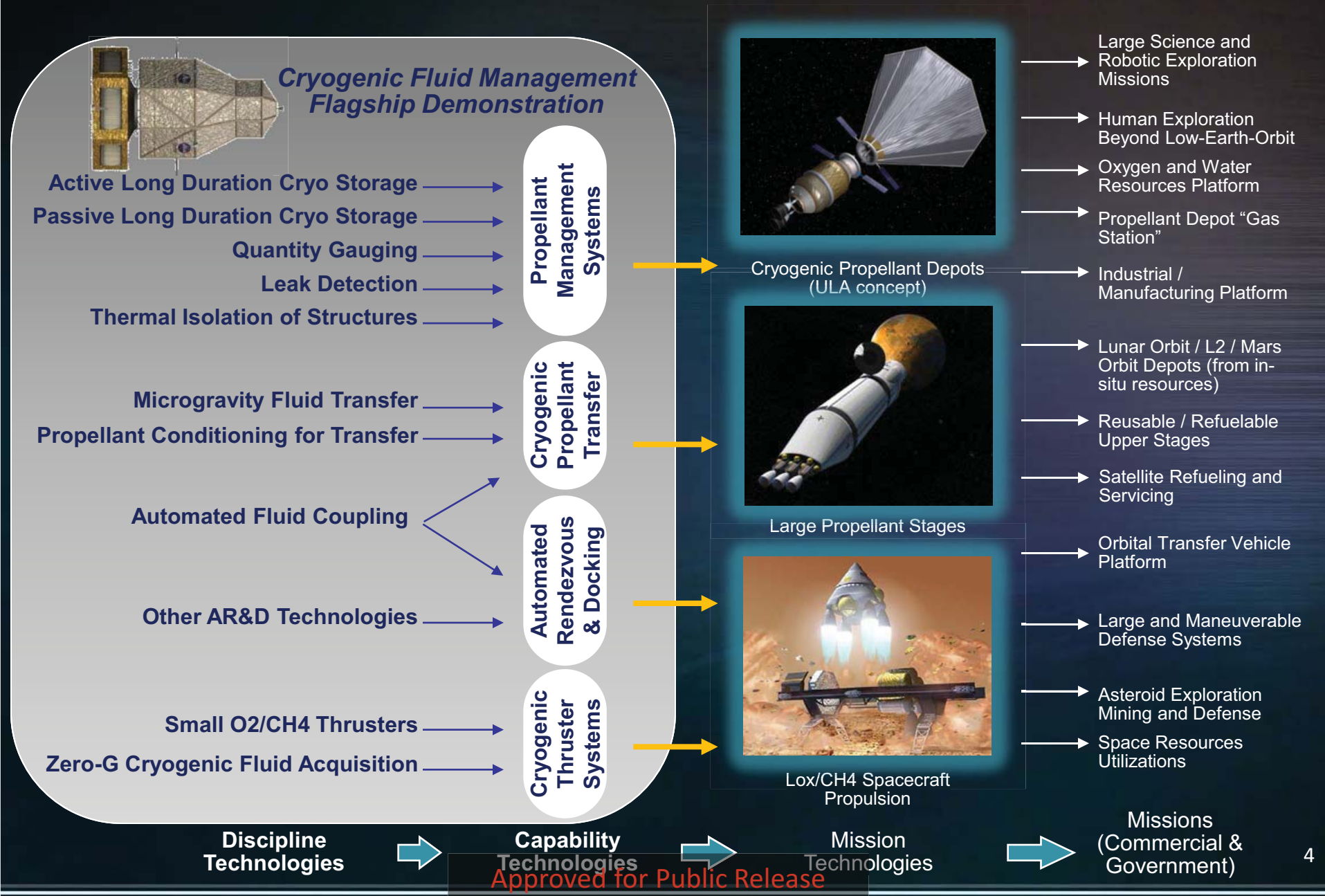
Power Generation and
Energy Storage



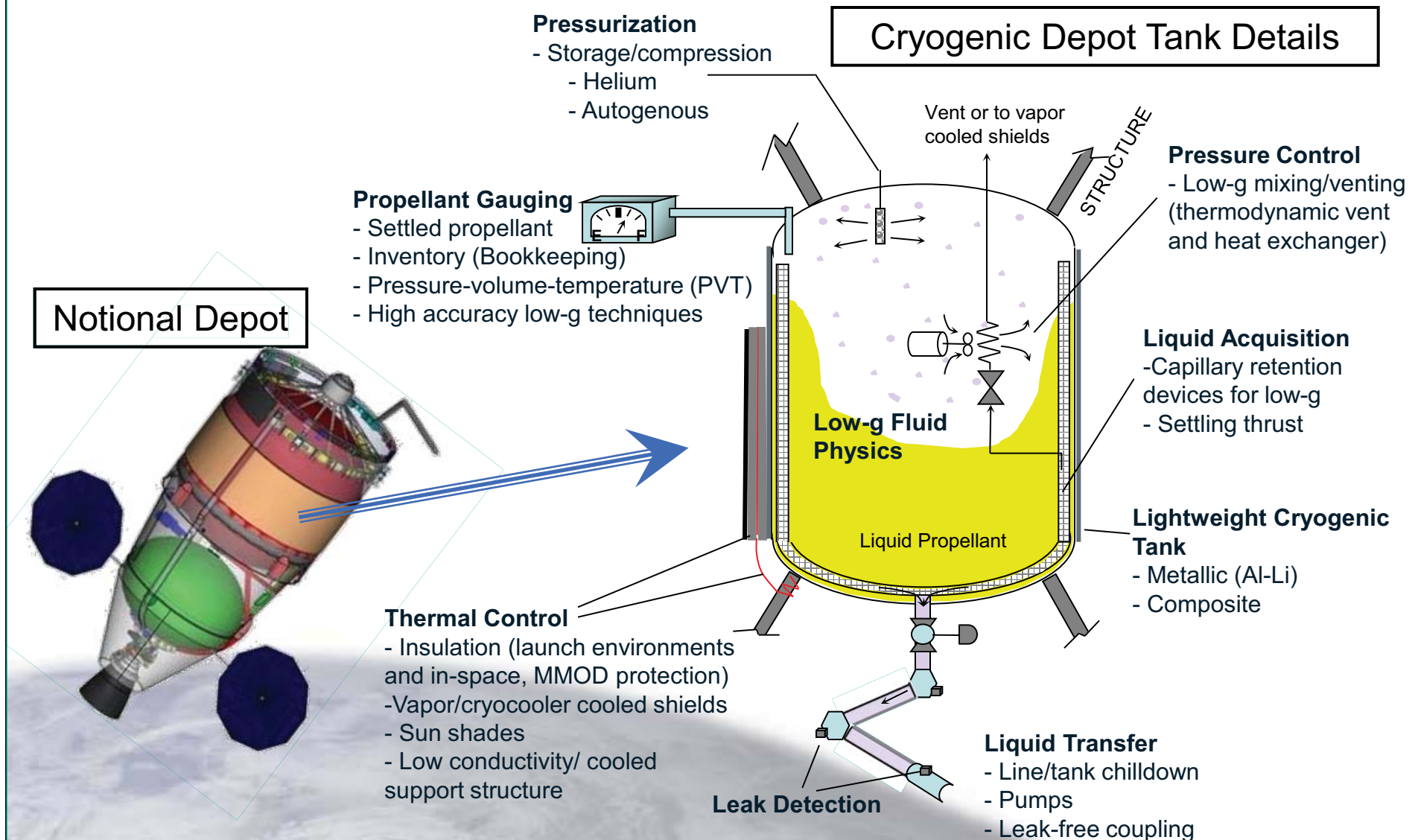
CPST Demonstration Mitigates Risks for Multiple Architecture Elements and Systems

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Purpose of CFM Demo: Support Future Missions

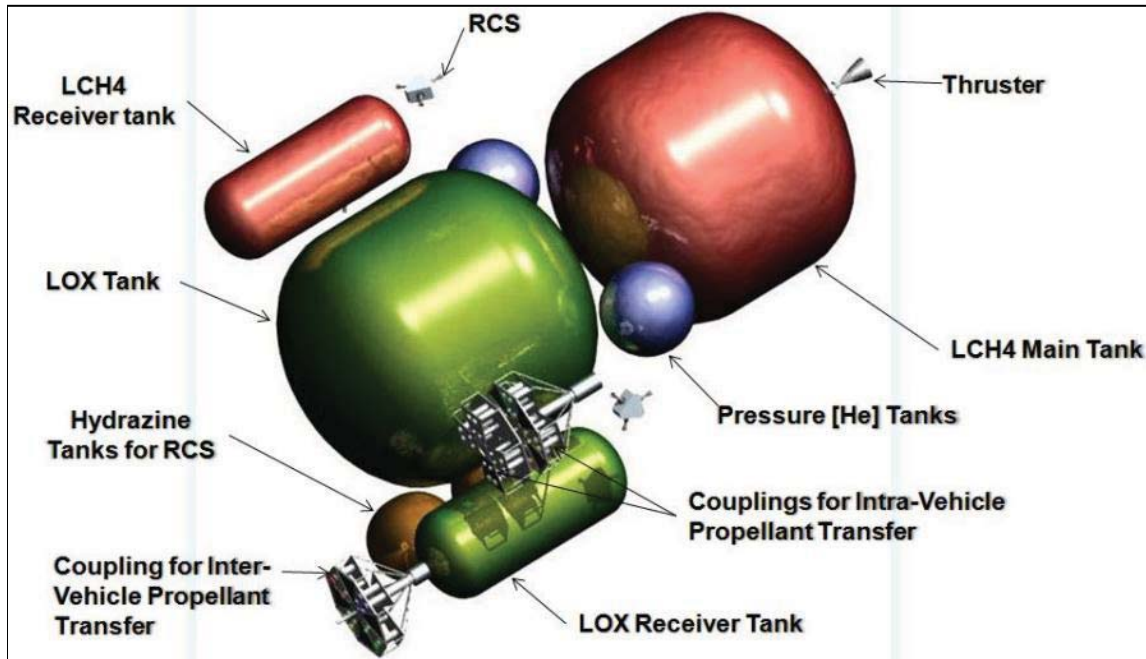


Cryogenic Propellant Depot CFM Technologies



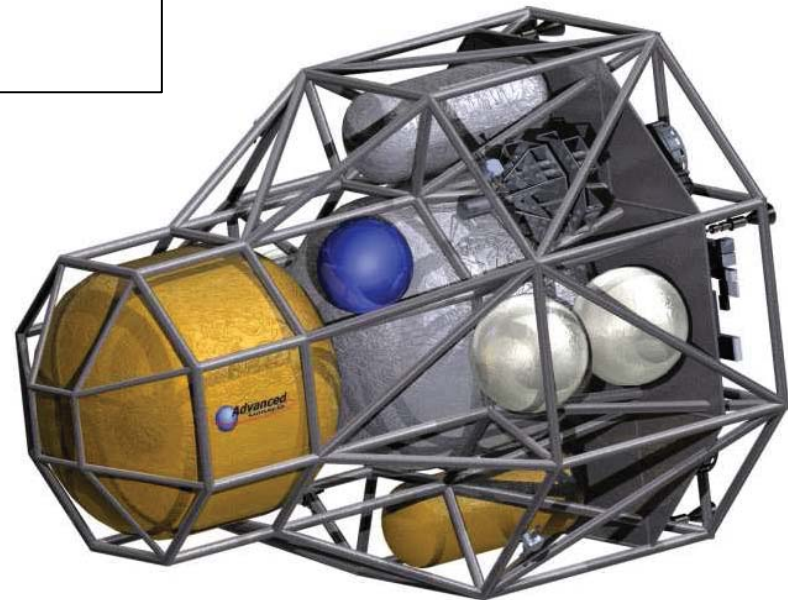
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Early Mission Concept Formulation



Methane-Oxygen Concept

Hydrogen-Oxygen Concept



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External input (Broad Area Announcement contracts)



- BAA Intended to get Industry input on technology objectives, mission concepts
 - 4 Contracts awarded (AMA, Ball, Boeing, Lockheed Martin)
 - 1 Space Act Agreement implemented (ULA)
- BAA requested
 - Mission Justification and Prioritized Objectives
 - Technology recommendations and maturation plans
 - Technology extensibility arguments
 - Mission Concept
 - Cost Estimate
- BAA Mission Concept Constraints
 - Target Mission Cost - \$200M (not including Government requirements)
 - Allowed to propose up to \$300M if significant added benefit identified
 - ATP in 2012 or 2013 if Technology Maturation identified as required
 - Flight 3 years from ATP
 - ~6 month mission duration

BAA Mission Objectives



BAA Mission Objectives

- **Cryogenic Fluid Storage**
 - Demonstrate approach for zero boil-off storage of liquid oxygen in microgravity.
 - Demonstrate approach for minimal boil-off storage, with a goal of zero boil-off, of liquid hydrogen in microgravity.
- **Cryogenic Propellant Acquisition**
 - Demonstrate approach for acquisition and bubble-free flow of liquid oxygen and liquid hydrogen in microgravity.
- **Cryogenic Fluid Transfer**
 - Demonstrate approach for transfer of liquid oxygen and liquid hydrogen in microgravity (settled and unsettled conditions).
- **Cryogenic Fluid Quantity Gauging**
 - Demonstrate approach for mass gauging of liquid oxygen and liquid hydrogen in microgravity.
- **Instrumentation**
 - Demonstrate approach for leak detection of liquid oxygen and liquid hydrogen in microgravity.
 - Demonstrate approach for flow measurement of liquid oxygen and liquid hydrogen in microgravity.
- **Tank Pressurization Methods**
 - Demonstrate approach for cryogenic tank pressurization and pressure control of liquid oxygen and liquid hydrogen in microgravity.

BAA Summary



- **5 Diverse Concepts Developed**
 - 1 Single Fluid (H₂) Concept
 - 1 Propellant Scavenged Concept
 - 1 DragonLab Concept
- **All concepts met constraints**
- **General consensus on objectives and priorities**
- **All identified need for Technology Maturation Effort before proceeding to flight demonstration development**

BAA responses in conjunction with NASA Point of Departure Study were basis for Mission Concept Review and satisfaction of KDP A

SRR/MDR Concept



- **CPST Project successfully conducted an SRR / MDR in September of 2013**
- **Concept was based on study of DragonLab mission identified in the reformulation studies**
- **Based on SRR/MDR results, CPST project proceeded to KDP B in December of 2013**

Cryogenic Propellant Storage and Transfer Technology Demonstration Concept Vision



Extending human reach into deep space by advancing cryogenic propellant storage and transfer technologies to meet the needs of both NASA exploration systems and commercial launch providers

*Passive Storage, Transfer,
and Gauging Demo*

Check-out

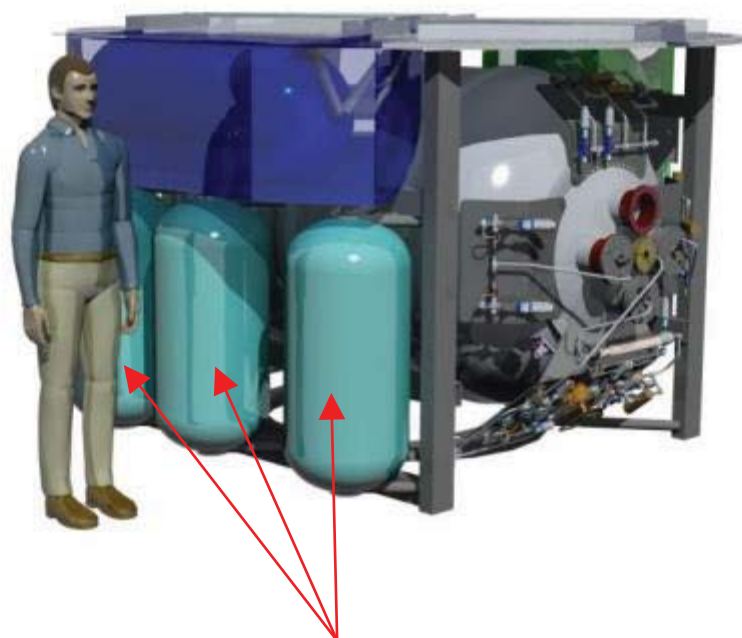
Dock to ISS

*Launch
2017*

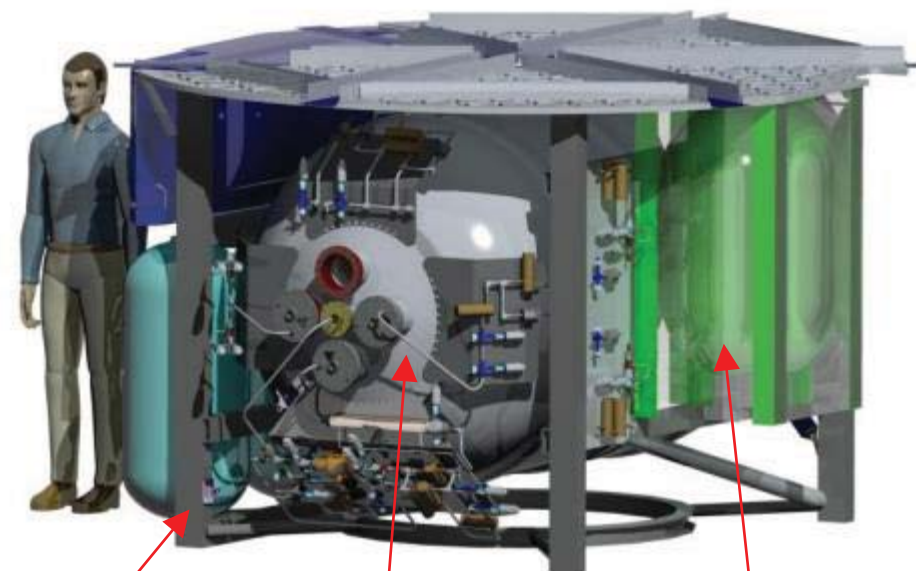
- *Demonstrate long-duration storage*
- *Demonstrate in-space transfer*
- *Demonstrate in-space, accurate gauging*

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DragonLab Concept (Launch Orientation)



GHe Tanks



Primary
Structure

Storage Tank
Assembly

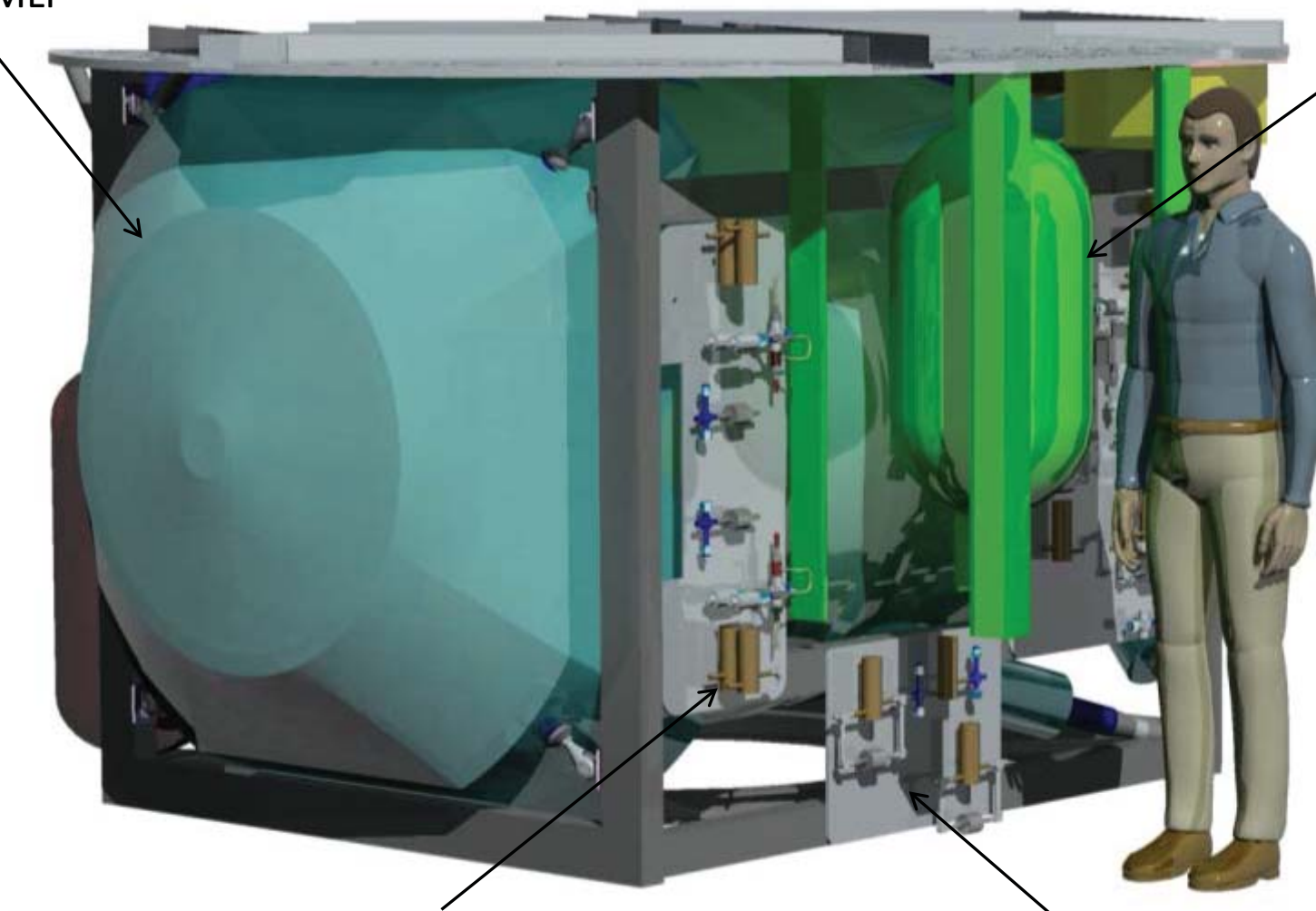
CNES Receiver
Tank Assembly
Envelope

Payload SRR/MDR Concept



SSMLI/MLI

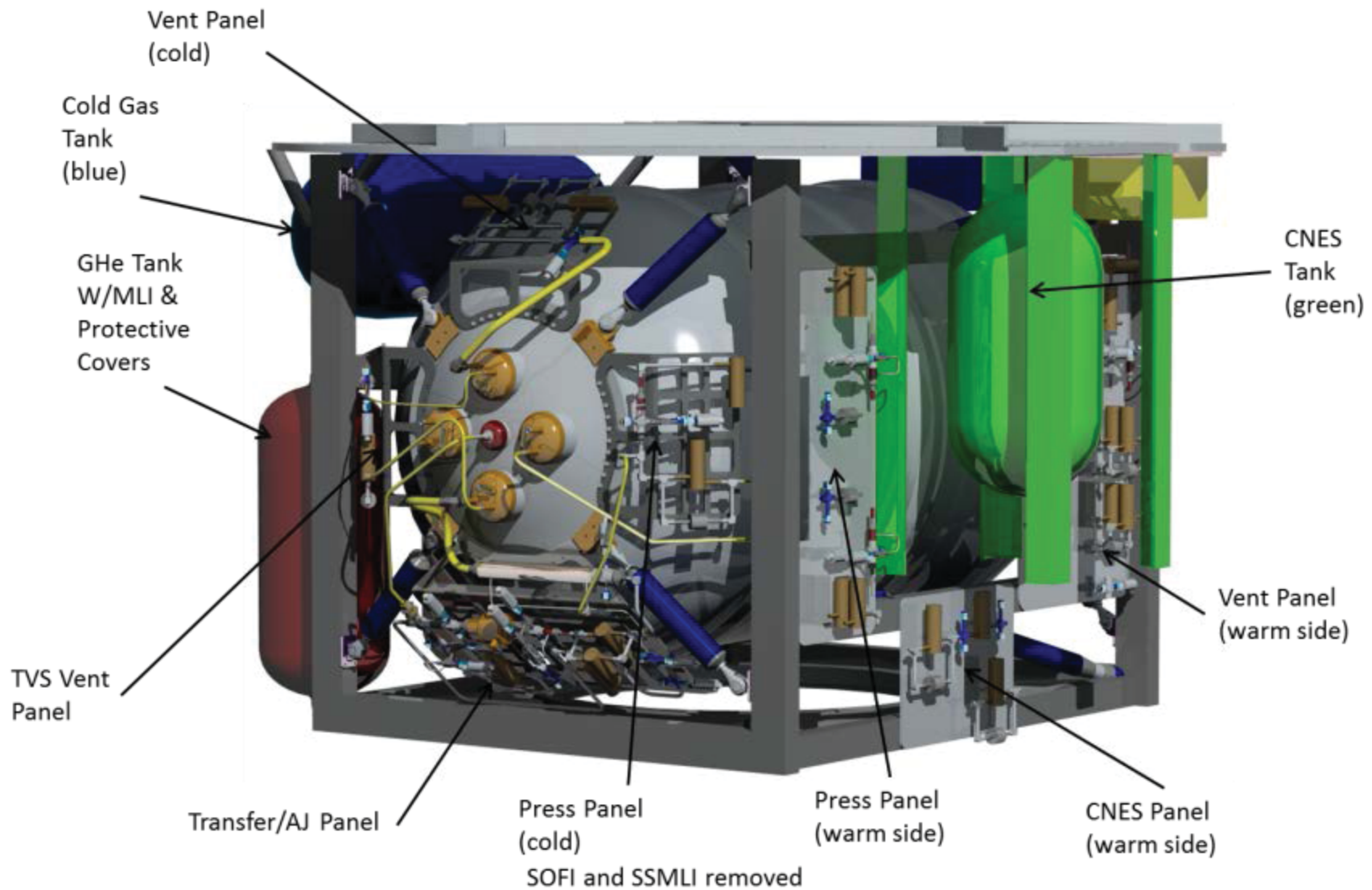
CNES
Tank
(green)



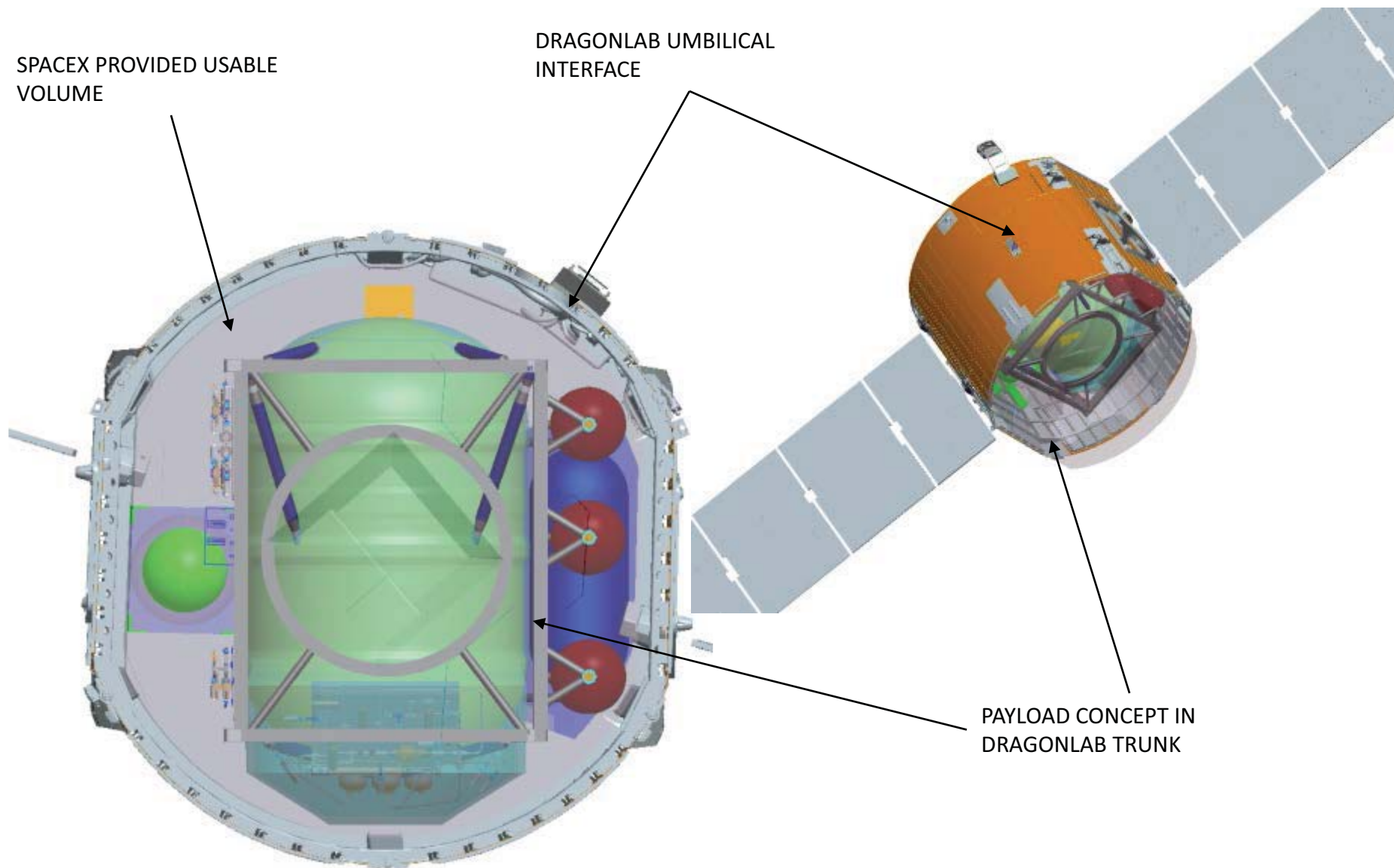
Press System
(warm side)

CNES
Component Panel

Payload Assembly Breakdown



CPST Payload installed in Dragon Trunk



Technology Maturation Phase Overview



Purpose:

Conduct tests, analytical modeling, and studies to mature technologies which were planned for the CPST demonstration flight in order to reduce the risk to cost and schedule for system development.

Scope:

The technology maturation phase addressed the following cryogenic fluid management technology areas:

- Thermal Control
 - “Thick” Multi-layer insulation (MLI) blanket penetration thermal losses
 - Reduced hydrogen boil-off with active thermal control
 - “Thick” Multi-layer insulation (MLI) for large scale tanks
 - Zero Boil-off oxygen storage
- Zero-g acquisition of cryogenic liquid for propellant transfer
- Chill-down of a propellant line for tank-to-tank transfer
- Zero-g propellant gauging
- Development and validation of analytical tools for thermal and fluid dynamic prediction of cryogenic propellant system storage performance

Thermal Control: Penetration Heat Leak Study



Objective:

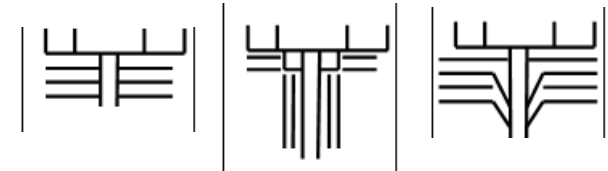
- Quantify thermal losses involving integrating MLI into real situations.

Approach:

- Test different integration methods & develop models specifically focused on the effects of penetrations (including structural attachments, electrical conduit/feedthroughs, and fluid lines) through MLI.

Results:

- Developed test method for measuring degradation of MLI around a penetration
- Measure heat load degradation and radius of thermally effected zone
- Determined the integration is best done with microfiberglass blankets
- Built & validated detailed thermal model of penetrations

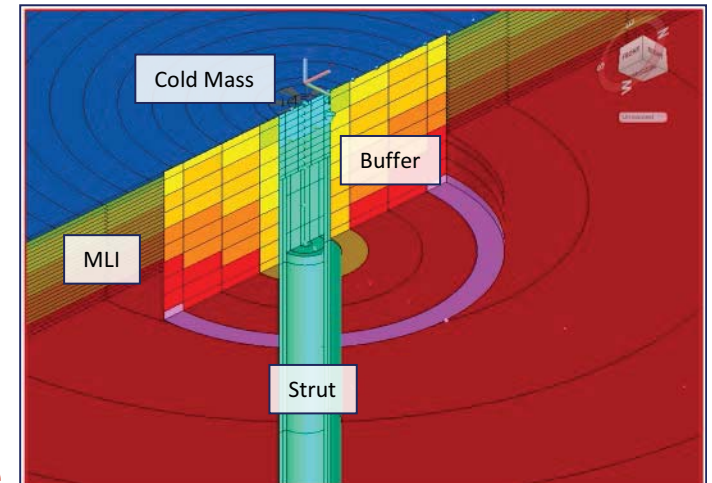


Comparison of Different Integration Approaches

Calorimeter Test
Setup at KSC



Thermal
Model



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Thermal Control: Hydrogen Reduced Boil-off



Objective:

Validate concept to reduce boil-off of LH2 by integrating a ~90K cryocooler to intercept heat in the MLI and conductive loads.

- Address both thermal and structural concerns

Approach:

Constructed identical subscale tank test articles with broad area cooling (BAC) shields inside a thick MLI blanket.

- Thermal test article integrated with a reverse turbo Brayton cryocooler.
- Structural test article exposed to launch representative acoustic environment
- Self supporting MLI evaluated in Phase II of testing

Results:

- Acoustic tests resulted in no damage to MLI/BAC system
- Thermal testing demonstrated ~60% reduction in boil-off



Thermal test article
being lowered into
thermal vacuum
chamber



Structural test article
in acoustic chamber

Thermal Control: Oxygen Zero Boil-off



Objectives

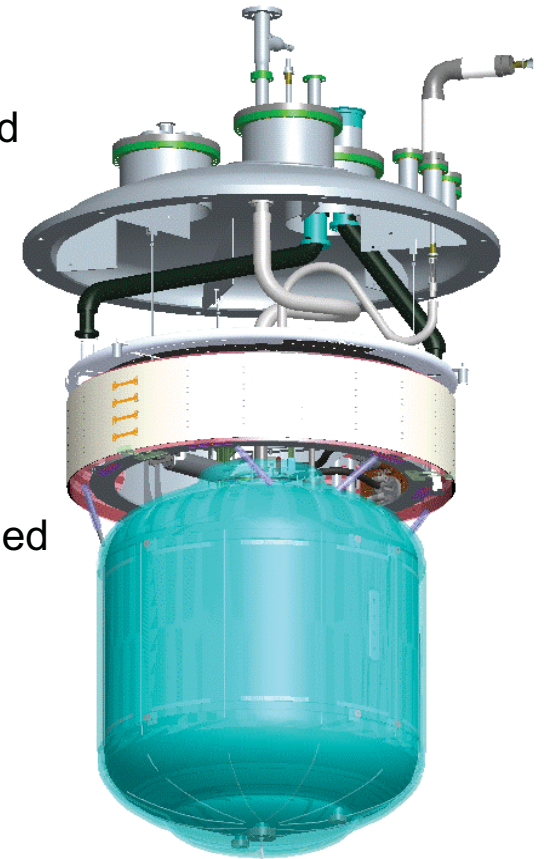
Quantify the system performance integrating a flight representative reverse turbo-Brayton cycle cryocooler for Zero Boil-Off (ZBO) storage of Liquid Oxygen (LO₂) for extended duration in a simulated space environment

Approach

- Liquid Nitrogen was used as a surrogate fluid for LO₂ to eliminate risks/costs associated with testing with LO₂; testing conducted at elevated pressure to simulate LO₂ storage temperature
- Test article included the following:
 - Flight representative test tank with circulator tubing stitch welded and epoxied to test tank; thick (74 layer) traditional MLI
 - Simulated space vacuum and thermal environment

Results

- Success in ground demonstration of active thermal control technologies that achieve ZBO of LO₂
 - ZBO achieved at two storage tank fill levels: ~ 90% and ~25% full



3-D image of test article for
LO₂ ZBO validation

Cryogenic Propellant Transfer: Transfer Line Chill-down



Objectives

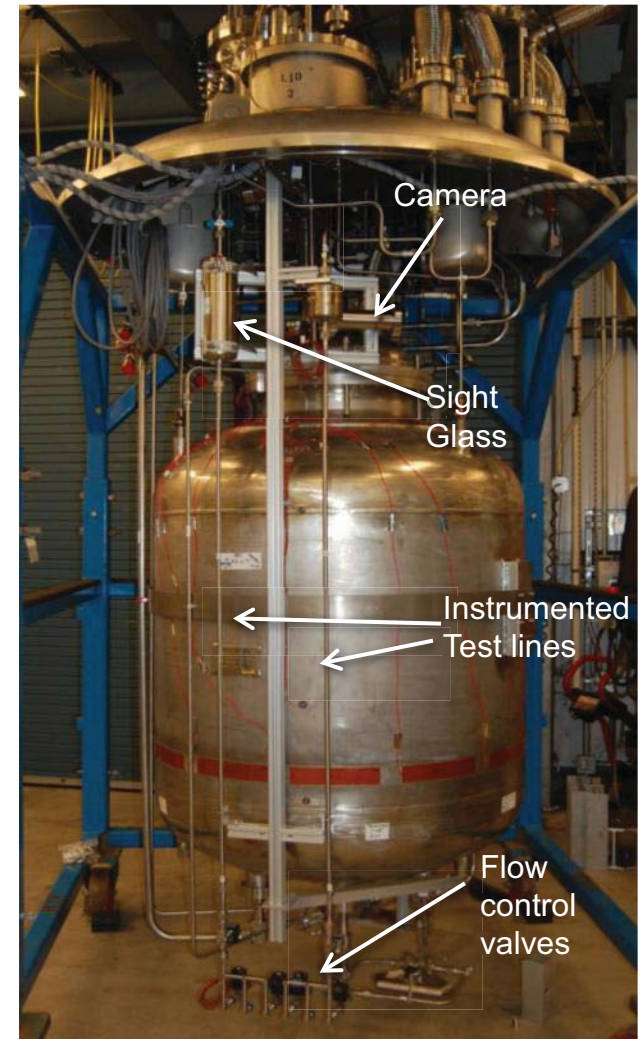
Evaluate efficient methods of pre-chilling a (tank-to-tank) transfer line of size representative of the CPST mission hardware.

Approach

- Construct a LH2 supply test tank with a transfer line of suitable diameter and length to roughly simulate the CPST system
- Test article included the following:
 - Vertical flow
 - Variable flow rates
 - Downstream flow visualization
 - Simulated space vacuum and thermal environment

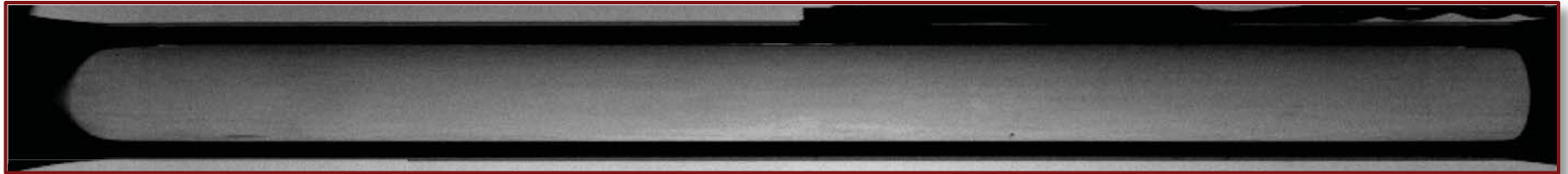
Results

- Successfully collected data on chill-down of the line varying several parameters.
- Compared temperature and pressure data to visual flow quality.
- Used data to develop simplified chill-down models.

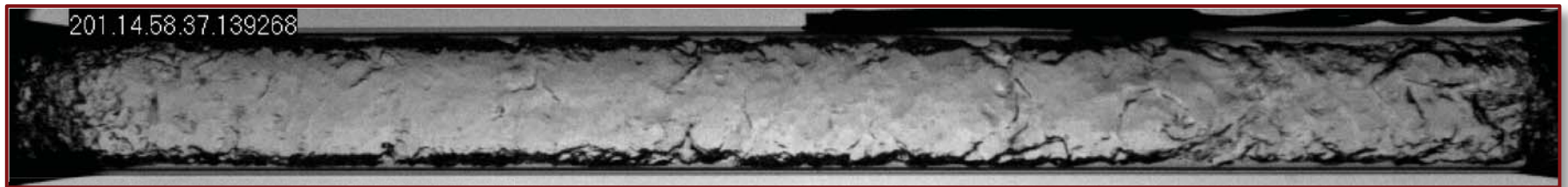


Line-Chill test article
prior to insulation

Propellant Transfer: Transfer line Chill-down Visualization



LH₂ Gas to Droplet



LH₂ Wavy Annular Flow



LH₂ Bubbly Flow

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Propellant Gauging: Radio Frequency Mass Gauge (RFMG)



Objective:

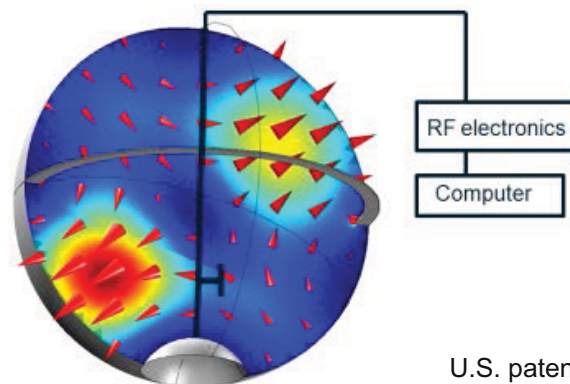
Continued maturation of a gauge technology capable of measuring the amount of liquid cryogenic propellant in the tanks of a vehicle in space without accelerating to settle the propellant

Approach:

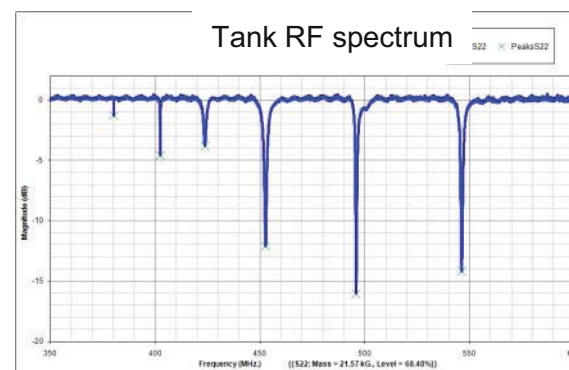
- Apply system developed in ground-based testing to a tank with a simulant fluid on a aircraft flying parabolic arcs for “zero-g”
- Mature electronics used for excitation and analysis of RF signal to enable a flight system.

Results:

- Successfully obtained microgravity data through multiple parabolic arcs and multiple configurations



U.S. patent # 8,353,209



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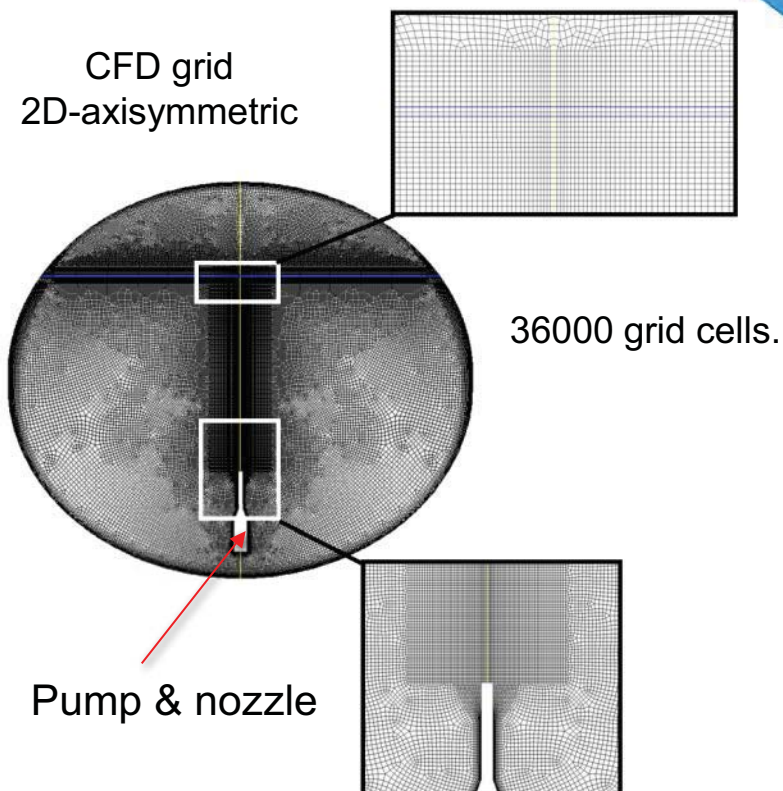
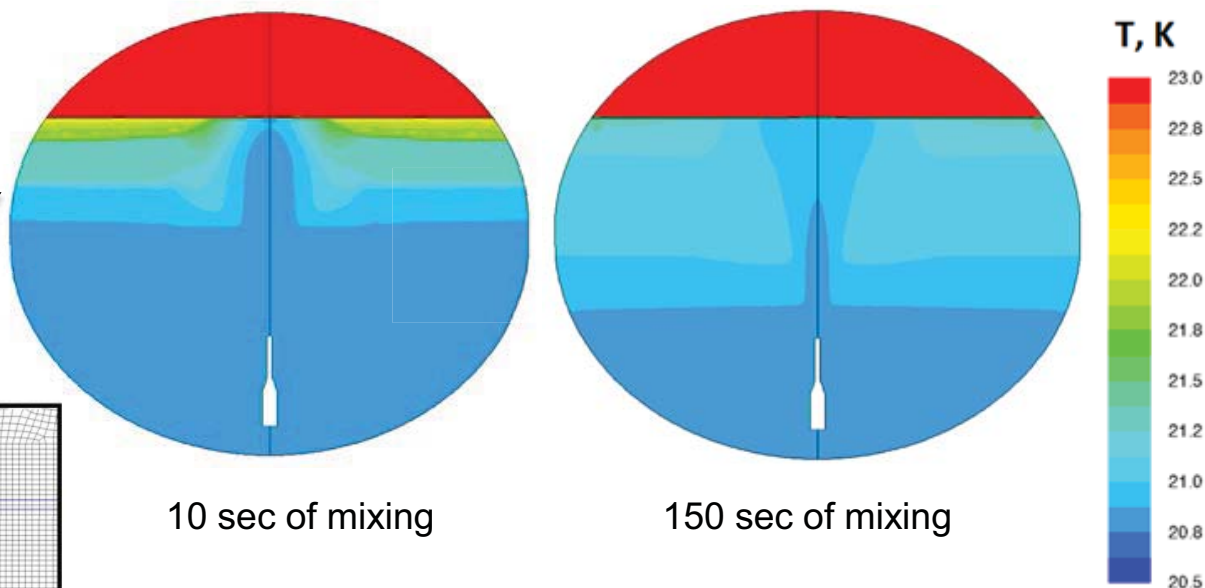
Analytical Model Development Example

Fluent Validation against LH2 Axial Jet Mixing

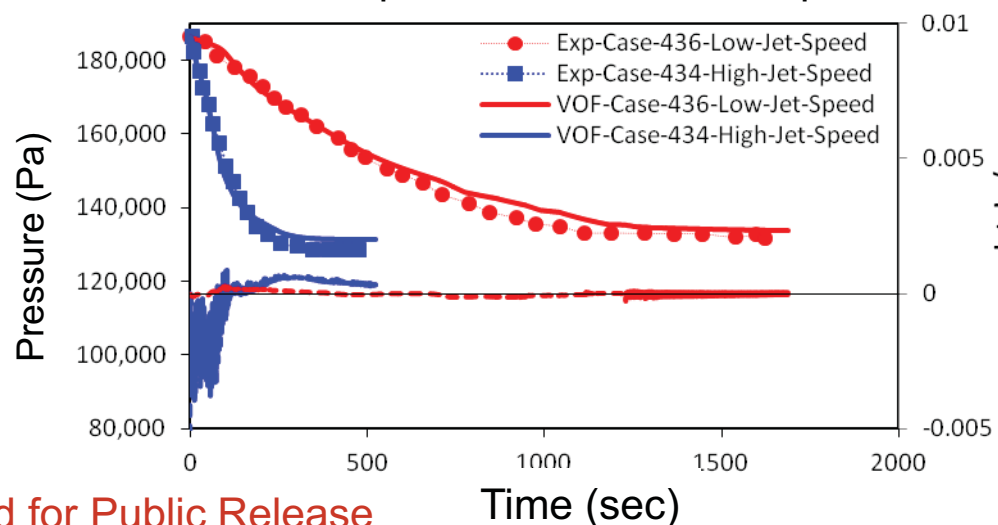


- Dia_tank = 2.2 m, Dia_jet = 2.21 cm
- 10 hrs self-pressurization simulated before axial jet is turned on (using uniform Wall Heat Flux= 4.2 W/m²)

Temperature contours “clipped” in ullage to show stratification in liquid



86% Liquid Fill: Effect of Jet Speed



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Summary



- The Cryogenic Propellant Storage and Transfer Technology Demonstration mission is being reformulated into a ground test activity.
- The Technology Maturation Phase of the mission was highly successful in raising the maturity of key technologies to reduce the risk of developing these systems for a flight demonstration. Advancements were made in:
 - Thermal control
 - Propellant transfer
 - Propellant gauging
- In addition, advancements were incorporated into NASA's analytical modeling for cryogenic fluid management systems.